TECHNICAL FIELD

.The present. invention relates to a method of noise whitening a received signal. In particular, but not

5   exclusively, it relates to a method for setting a prefilter for an equalizer of a demodulator in a wireless communication system with noise whitening to suppress co-channel and adjacent channel interference.

10   ### BACKGROUND OF THE INVENTION

In wireless digital TDMA communication systems, such as GSM, EDGE and D-AMPS, data is transmitted in the form of bursts, the bursts comprising a plurality of symbols. The symbols may be altered or distorted during

15   transmission by various factors such as bandwidth-limited modulation and co-channel and adjacent channel interference which occur during multipath signal propagation. This distortion is referred to as the Inter Symbol Interference (ISI). Therefore, it is desirable

20   that the demodulator of a receiver of such a communication system can compensate for ISI. Equalizers are used extensively for this purpose.

The performance of wireless TDMA systems is also limited by interferences from other users in the same

25   system. Users in a neighbouring cell transmitting at the same carrier frequency create co-channel interferences

(CCI) while users transmitting at adjacent carrier
frequency create Adjacent Channel Interferences (ACI).
Unlike background noise, these interferences pose as
"colored" noise.

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When a wireless link, such as in GPRS/EGPRS, is used
for a data transmission, higher equalizer performance is
required, since data transmission is much more error
sensitive than voice transmission. To avoid information
10 loss, a wider receiver filter (a Nyquist filter) can be
used, and at the same time suppress both co-channel and
adjacent channel interferences by whitening the noise.
Noise whitening therefore greatly enhances the
performance of equalizers.

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In practice, noise whitening is accomplished
together with a prefilter; otherwise the composite
channel will be much longer than the propagation channel,
resulting in significant performance degradation. The
20 prefilter, also known as a WFM (a Whitened Matched
Filter), FFF (a FeedForward Filter) or precursor
equalizer is fundamental to the performance of most
widely used equalizers, such as MLSE (Maximum-Likelihood
Sequence Equalizer), DFE (Decision Feedback Equalizer)
25 and DFSE (Decision Feedback Sequence Equalizer). The role
of the prefilter is to equalize precursor ISI (ISI from

future symbols), convert a non-minimum phase channel into

a minimum-phase one, compact the energy of the delay

spread symbol as much as possible to the first few taps

to increase the effective decision point SNR (Signal to

5   Noise Ratio) for the equalizer.

    For non-minimum phase channels, a prefilter is non-

causal and infinite in length. In reality, the prefilter

is always approximated with a finite length n-tap FIR

10 (Finite Impulse Response) filter. To get satisfactory

performance, n must be significantly longer than the

length of channel impulse response m, i.e. $n >> m$. As a

rule of thumb, the length of the prefilter can be chosen

as

15                    $$n = 2m + 3$$

    Noise whitening, prefilter setting and updating

represents a significant, and often dominate portion of

the equalizer complexity.

    There are two approaches to noise whitening, namely

20 explicit and implicit. In the explicit approach a

dedicated filter w is calculated from the noise estimate

by solving the following

                    $$Rw = \rho$$

where ρ is an estimate of the noise auto-correlation and

25 R is a Toeplitz matrix of the estimate. The drawback of

the explicit whitening is that the order of the whitening

filter must be very low to keep the length of the

composite channel short. This has limited the modelling

capability and performance of this approach. In addition,

5   a separated prefilter is still necessary, which further

increases the complexity in the signal processing of the

received signal.

In the implicit approach, the whitening is done in

10   prefilter setting. There are two approaches to prefilter

setting: MMSE (Minimum Mean Square Error) and ZF (Zero-

Forcing, a.k.a. Minimum Phase or All-Pass filter). The

MMSE approach includes numerous matrix operations,

including multiplication; factorisation and inversion

15   which have to be applied to matrices of size $(n+m) \times$

$(n+m)$, for example the noise whitening prefilter settings

are derived as follows:

$$f = d_{n-1} \mathbf{u}^* \mathbf{L}^{-1} \mathbf{H}^* \ \mathbf{R}^{-1}$$

where d_{n-1} is the (n-1)th element of a diagonal matrix;

20   $\mathbf{L}$ is the low triangle matrix; $\mathbf{H}$ is an $(n+m) \times (n)$

channel matrix; and $\mathbf{R}$ is a $(n \times m)$ noise correlation

matrix. The triangular $\mathbf{L}^{-1}$ is obtained by a

symmetrical factorisation as follows:

$$X + \mathbf{H}^* \mathbf{R}^{-1} \mathbf{H} = \mathbf{LDL}^*$$

where X is the data correlation matrix of size

$(n+m) \times (n+m)$ and H and R have dimension $(n+m) \times n$ and

$n \times n$ respectively, $(\circ)^{*}$ denotes conjugate transposition.

LDL^{*} are the lower triangle L, diagonal D and upper

5   triangle L^{*} of the symmetric factorisation of the

Toeplitz matrix. An example of noise whitening prefilter

design by spectral factorisation is disclosed by WO

02/33923.

10   Known methods in ZF approach, not comprising noise

whitening, includes Root Searching via Newton Raphson

iterations and Spectral Factorization via Iterative

Backsubstitution (SFIB). Some numerical difficulties have

been accounted in the root searching method when it is

15   implemented in fixed-point arithmetic operations,

partially due to the rounding errors in the deflation

process. Spectral factorisation is a classical problem in

control theory, where considerable efforts have been made

for its solution. However, almost all the proposed

20   algorithms are targeted on reducing the asymptotic

complexity, where a solution with $O(m^{2})$ operations, where

$O(x)$ is the asymptotic prepositional to x, is considered

good, regardless of the constant factor (for example the

number of iterations). For SFIB method, an experimental

25   iteration of 20 is considered sufficient in an EDGE

equaliser. Beside computational complexity, another

drawback of SFIB is that a final scaling is always

necessary since the result of the iteration oscillates

between two sets of initiation-dependant values.

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The MMSE approach, which often includes noise

whitening, is computationally expensive since numerous

matrix operations, including multiplication,

factorisation and inversion have to be applied. The

10   classical MMSE approach is disclosed, for example, in N.

Al-Dhahir and J.M. Cioffi "MMSE Decision-Feedback

Equalizers: Finite-Length Results", IEEE Trans. on

Information Theory, vol.41, no.4, July 1995.

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SUMMARY OF THE INVENTION

The object of the present invention is to provide a

method for noise whitening suitable for prefilter setting

in which the noise whitening computation is simplified to

20   reduce the complexity of the equalizer and hence reduce

the memory requirements and power consumption of such

equalizers. This is, for example, accomplished via a

simple polynomial operation of noise autocorrelation on

the prefilter, which is in turn obtained by a

25   computationally efficient band symmetrical factorisation.

The simplicity of the method of the present invention is

particularly advantageous for upgrading existing GSM

equalizers.

The noise whitening method of the present invention

5   in prefilter setting via a band symmetric factorisation

provides an approximation of the spectral factorisation

that is especially suitable for equalizer application in

digital communication systems.

10   According to an aspect of the present invention,

there is provided a method of noise whitening a received

signal, the method comprising the steps of: estimating

the noise of a channel; calculating the power spectrum of

the channel; adding the estimated noise and the

15   calculated power spectrum to build a positive definite

band matrix; applying symmetric factorisation to the

matrix; deriving the spectral factorisation of the

channel from the symmetric factorisation; approximating

the spectral factorisation; calculating the settings for

20   a noise whitening prefilter from the approximated

spectral factorisation and the estimated noise of the

channel; and prefiltering the received signal to noise

whiten the signal.

25   The effectiveness of the present invention is

partially due to the combination of approximation of the

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spectral factorisation and the noise of a channel. This

enables the positive definite band matrix to be generally

small, thus improving the computational efficiency of the

noise whitening.

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The power spectrum may be calculated by autocorrelation

and the symmetric factorisation may be square-root-less

Cholesky factorisation. The spectral factorisation can be

approximated by reversing the non-zero elements of the

10   last row of the decomposed lower triangle of the matrix.

The method of the present invention is particularly

suitable for generating the settings for a prefilter of

an equalizer.

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The accuracy of the approximation can be adjusted by

the size of the band matrix. The present invention

provides a noise whitening approach through direct

polynomial division of the estimate of the noise auto-

20   correlation by the prefilter setting which is obtained

from an approximation of channel spectral factorisation.

BRIEF DESCRIPTION OF DRAWINGS

Figure 1 is a simplified block diagram of a Decision

25   Feedback Sequence Equalizer (DFSE) of a preferred

embodiment of the present invention;

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Figure 2 is a flow chart illustrating the method of

the preferred embodiment of the present invention; and

Figure 3 is a graph illustrating the performance of

an equalizer having a prefilter of the preferred

5 embodiment of the present invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

A preferred embodiment of the present invention will

now be described with reference to Figure 1. In a mobile

10 communication system, a transmission sent in bursts, for

example GSM, is received and the transmission is

demodulated at the receiver. The demodulator includes a

DFSE equalizer 100 as shown in Figure 1. Although a DFSE

equalizer is illustrated here, it is understood that any

15 equivalent type of equalizer may be utilised.

The equalizer 100 comprises a burst synchroniser

110. The input of the burst synchroniser 110 is connected

to the input of the equalizer 100. The output of the

20 burst synchroniser 110 is connected to the input of an m-

tap channel estimator 120 and connected to the input of a

whitening prefilter 140. The setting of the whitening

filter 140 is controlled by a prefilter setting means

130. The output of the whitening prefilter 140 is

25 connected to the input of a sequence estimator 150. The

output of the sequence estimator 150 is connected to the

output of the equalizer 100.

    Operation of the equalizer will now be described.

5   The equalizer generates estimated symbols from the

    transmitted symbols of the received signal which may have

    become distorted during transmission. The transmitted

    symbols may have been distorted by a number of factors,

    for example the symbols may have altered by the

10 components (filters) of the transmitter of the

    communication system, distortion from the multipath

    channel during transmission to the receiver or the

    components of the receiver, for example the down

    conversion and analogue to digital conversion of the

15 received signal. The transmission may be also corrupted

    by background noise and strong interference from other

    users in the system, such as CCI and ACI.

    The received transmission bursts are

20 synchronised and forwarded to the m-tap channel estimator

    120 and the whitening prefilter 140. The m-tap estimator

    120 generates an m-tap channel estimate **h**. The m-tap

    estimate **h** is provided to the prefilter setting means

    130. The prefilter setting means 130 computes the noise

25 whitening in accordance with the method of the present

    invention as described in more detail below with

reference to Figure 2. The noise whitening f is then

utilised to set the whitening prefilter 140.

The burst synchroniser 110 synchronises the received

5   transmission bursts to be filtered by the whitening

prefilter 140 once the prefilter has been set. The

prefiltered burst is then provided on the input of a

sequence estimator 150 which is also provided with an

approximation of the channel spectral factorisation g.

10   The sequence estimator 150 generates an estimate of the

distorted symbols within the received transmission bursts

on the output of the equalizer.

The method of noise whitening according to a

15   preferred embodiment of the present invention will now be

described with reference to Figure 2.

In accordance with the method of the preferred

embodiment of the present invention, the noise power

20   spectrum p' of a channel is estimated, step 201. The power

spectrum p of the channel is also calculated, step 202.

When an m-tap channel estimate h is available, the power

spectrum of the channel can be calculated simply by

autocorrelation.

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$$p_i = \sum_{j=0}^{m-1-i} k_j^* h_{j+i} \qquad i = 0, \ldots, m-1$$

The estimated noise contribution is added to the

power spectrum, step 203,

5 $$s = p + \rho$$

s is used to build a positive definite band Toeplitz

matrix of size $k \times k, k \geq m$, step 204,

$$
A = \begin{bmatrix}
s_0 & s_1^* & \cdots & s_{m-1}^* & 0 & \cdots & 0 \\
s_1 & s_0 & \cdots & s_{m-2}^* & s_{m-1}^* & 0 & \cdots \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\
s_{m-1} & s_{m-2} & & s_0 & \cdots & \cdots & s_{m-1}^* \\
0 & \cdots & \cdots & \cdots & \cdots & \cdots & s_{m-2}^* \\
\cdots & 0 & s_{m-1} & \cdots & \cdots & s_0 & \cdots \\
0 & \cdots & 0 & s_{m-1} & \cdots & \cdots & s_0
\end{bmatrix}
$$

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A symmetric factorisation (a.k.a square-root-less

Cholesky factorisation) is then applied, step 205,

$$A = LDL^*$$

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The spectral factorisation can then be approximated

by reversing the non-zero elements of the factored low

triangle L, step 207.

20 $$g = flip(L(k-1, k-m:k-1))$$

The root accuracy of the approximation is affected
by the dimension of the matrix A. The approximation of
the spectral factorisation is such that g is minimum

5 phase (i.e. all its roots are within the unit circle in a
complex plain) with correct scaling.

Implicit noise whitening according to the preferred
embodiment of the present invention is formulated by a

10 direct polynomial division, step 208.

$$f = \left(\frac{h}{g}\right)^* \bigg/ \rho$$

The result is stable since both channel spectral
factor g and the autocorrelation of the noise estimate

15 ρ, which can be obtained in channel estimation stage, are
causal and invertible. Furthermore, due to the method of
calculation of both g and ρ in accordance with the
present invention, the band Toeplitz matrix A need not
be too big, for example, $k = m+1$ will often be sufficient.

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Therefore, computational efficiency is greatly
improved. It is more than an order of magnitude simpler
than the classical MMSE approach. Furthermore, compared
to the explicit whitening approach, the computational

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efficiency advantage is due to several factors. First, no

explicit whitening filter needs to be calculated, which

saves computation in both solving $Rw = \rho$ and processing

the receiver signal. Second, for all channel conditions

5   in e.g. GSM/EDGE systems, channel spans only 4-8 symbols.

Thus, the spectral factorisation via $A = LDL^*$ requires

much less operations than the SFIB approach.

Figure 3 illustrates a graph of the performance of

10   an equalizer including the noise whitening prefilter

whose settings are derived according to the method set

out above. A comparison is made of the block error rate

(BLER) and channel interference C/I for two interference

environment, namely co-channel interference (CCI) and

15   adjacent channel interference (ACI) using an MCS9, ratio-

1 coding scheme in TU3, typical urban, 900MHz with no

frequency hopping system. As illustrated in Figure 3 in

a CCI environment, a 1dB gain is achieved by a noise

whitening prefilter set by the method of the present

20   invention and, in the ACI environment, a 5dB gain is

achieved by use of a noise whitening prefilter set by the

method of the present invention.

Although a preferred embodiment of the method of the

25   present invention has been illustrated in the

accompanying drawing and described in the forgoing

detailed description, it will be understood that the

invention is not limited to the embodiment disclosed, but

is capable of numerous variations, modifications without

departing from the scope of the invention as set out in

5   the following claims.